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An Investigation of Fatigue During the Flexion and Extension of the Knee as a Function of Velocity

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ABSTRACT

This paper describes the work intended to supplement a previous study of Extravehicular Mobility Unit (EMU) strength fatigue data, collected from a variety of joints at a fixed velocity (60 degrees/second), by collecting torque data of a single joint (knee) over time, unsuited, under a condition of multiple fixed velocities. Knee flexion and extension torque values were evaluated for 8 subjects at 60, 120, 180, and 240 degrees per second. Subjects were considered "fatigued" when they reached 30% of the maximal voluntary contraction (MVC), or after 5 minutes of testing had elapsed.

Results indicated that over the five-minute testing period, subjects' available torque output decreased to 40% of their MVC, and then reached a plateau at this level. For lower velocities, subjects gradually decreased from their MVC, but their overall decrease in torque over the five-minute period was high. For higher velocities, subjects experienced a sharp decline in torque output at the beginning of the trial, but quickly reached a plateau and had an overall smaller decrease in torque compared with lower velocities. Subjects were able to maintain a more constant torque at higher velocities at the beginning of a trial. These results will be correlated to the EMU data when it has been collected and processed, and a mathematical fatigue model will be built to aid designers and mission planners in evaluating EVA activities.

INTRODUCTION

During spaceflight, astronauts engage in extravehicular activity (EVA) while donning an Extravehicular Mobility Unit (EMU), or space suit. Because of the duration of the EVA activity, as well as the constraints of the EMU, astronauts could experience severe joint and muscle fatigue during these missions. In addition to being a safety concern for crewmembers, fatigue may also result in an unsuccessful EVA and therefore an unsuccessful mission. There are numerous benefits to developing a modeling system that can predict not only the astronaut's movements during an EVA, but also his/her level of fatigue. This modeling system could help predict whether a certain activity will overload the crewmember, as well as help mission planners design missions. In addition, it could be used in training to guide crewmembers in maintaining the same level of effort throughout an activity.

This study was conducted as a supplement to a broader study measuring joint fatigue in both the suited and unsuited conditions. The parent project, known as the EMU Fatigue study, is measuring the level of fatigue of major joints in both isometric and isokinetic conditions. Due to time constraints, all of the data collection of the EMU Fatigue study was done at a single velocity. It does not, therefore, investigate the effect of velocity on joint fatigue. The purpose of this supplemental study is to collect similar data, limited to knee flexion and extension, at a variety of velocities. Since no EMU data exists on the relationship between velocity and joint fatigue, this preliminary study was limited to a single joint. This data can be used in conjunction with the EMU Fatigue data for future studies in creating computer-generated models, as well as designing a more efficient EMU and developing more efficient hardware to be used in a space environment.

BACKGROUND & SIGNIFICANCE

Muscle fatigue has been studied for a number of years, but only a small amount of work has been done on joint fatigue. While variations exist in the definition of fatigue and testing methods employed by different researchers, fatigue description and measurement techniques used in this study will be based on previous studies that encompassed similar goals and objectives. Additional background research information in muscle fatigue can be found in *An Extravehicular Mobility Unit (EMU) Strength and Fatigue Data Collection Test Plan* [1], the NASA Test Plan Document that precedes this study.

Jaric, *et. al*.[2], found that agonist muscle fatigue affects movement velocity more than antagonist muscle fatigue. A study by Spendiff [3] revealed that exercise at a lower velocity had a greater diminishing effect on mean and peak torque production in subsequent exercise over increasing velocities. It also showed that torque is more diminished at the higher velocities, possibly at velocities close to the optimal force-velocity relationship. B. Gerdle, *et. al.* [4], showed that a significantly higher degree of fatigue was found at a low rather than at a high torque level. Another study by B. Gerdle and M. Langstrom [5] concluded that the relative contraction work decline increased with angular velocity. This study establishes that there is a definite relationship between fatigue and angular velocity with regards to contraction work, but states that peak torque and mean power decreases are not velocity dependent. McCartney [6] and Jones [7] both state that a higher velocity is associated with a greater relative decrease in power than a lower velocity.

Barnes [8] investigated knee extension at 60, 120, 150, and 300 degrees/second, but tested subjects for only 10 consecutive extensions. This was considered fatiguing during his study based on the statistically significant decrease between the first and final trial, but is not the long-term fatigue that this current study is addressing. Barnes found that the isokinetic fatigue curve for knee extension was linear during the initial stages of the process, and the fatigue curves were essentially identical regardless of velocity. Kues [9] also addressed knee extensor torque at a variety of test conditions–isometric contractions at 40 and 60 degrees of knee flexion, concentric and eccentric isokinetic contractions at 30, 90, 120, and 180 degrees/second—and found that correlation coefficients decreased as the difference between velocities of the isokinetic movements increased. These results suggest that high-velocity and low-velocity isokinetic testing may be assessing some different components of performance.

Rizzardo et al [10] addressed eccentric and concentric torque and power in females and found that both concentric and eccentric power increased with increasing velocity of the contraction. Perrine [11] concurred with this finding by determining that the greatest instantaneous power output was attained and remained constant over the three highest test velocities addressed by that study—192 to 288 degrees/second. In a cycling study by Beelen et al [12], however, it was found that fatigue (after 6 minutes of cycling at 90% maximal O2 uptake) did not cause a significant reduction in maximal peak power at lower velocities of 60 and 75 rpm. However, at the higher velocities of 90, 105, and 120 rpm there was a significant reduction in power after fatigue, ranging from 23 to 28%. This concurs with McCartney [6] and Jones [7].

In this study, dynamic joint strength and fatigue data in an unsuited condition was collected and processed. It has been established that at a maximal effort, torque is inversely related to velocity. However, it is unknown if this relationship is sustained when the subject reaches a certain level of fatigue. A generic methodology for quantifying the differences between and within the unsuited and suited conditions has been established via a previous pilot study by Morgan *et al.* [13]. The results of this current study are expected to impact several areas of EMU-related work. The designers of new suits will be better able to understand, and therefore optimize, the crewmembers' ability to exert force at varying velocities. The EMU computer modeling system previously mentioned could eventually be used to extrapolate suited strength and fatigue parameters from data gathered under unsuited conditions. By combining these strength and fatigue parameters at all of the testing velocities, the most efficient fatigue/velocity ratio can be established.

OBJECTIVES

The purpose of this study is to observe the effect of varying velocities on a subject's joint fatigue level. Fatigue is measured as the percent of torque applied at a certain time with respect to the maximum voluntary contraction (MVC). The goal of this study is to determine whether the relationship between velocity and joint fatigue is linear, non-linear, or non-functional.

By understanding the relationship between velocity and torque during fatigue, suit and hardware engineers can work together to create an optimal working environment for the astronauts participating in EVAs. Mission planners can also use this information when scheduling the various activities that the astronauts are to perform during an EVA. Eventually, it may be possible to build a biomechanically sound model that predicts human capabilities and limitations under realistic work conditions.

METHODOLOGY

SUBJECTS - A group of eight subjects, consisting of four males and four females, participated in this study. All subjects had passed an Air Force Class III Physical, and had been cleared by the NASA Human Test Subject Facility for participation in this study. Subjects ranged in age from 21 to 46, and in stature from 162 to 188.1 centimeters.

APPARATUS - The primary testing apparatus was the LIDO Multi-Joint II testing unit (Loredan Biomedical, Inc., West Sacramento, CA). The LIDO Multi-Joint II is an integrated system consisting of a dynamometer connected to a personal computer. The system has a series of attachments that enable strength measurements of the various joints of the human body. The computer provides the operator with precise control of the actuator head during various modes of operation (isokinetic, isometric, etc.). The system follows experiment-defined exercise parameters: velocity, range of motion (ROM), and torque limits. A unique feature of the LIDO is that it incorporates a gravity compensation feature, which takes into account the one-gravity artifact throughout the ROM. This capability is used to remove the effect of the weight of the LIDO attachment and the subject's limb from the measured torque and forces, thus ascertaining the subject's true exertions. An additional data acquisition computer was connected to the LIDO to provide real-time display of the test parameters (angular position/velocity, torque, force, time, repetitions) plus facilitate post-test data analysis.

In addition to the data collected from the LIDO Multi-Joint II and the secondary data acquisition computer, every trial was recorded by video camera and stored on videotapes according to subject number.

EXPERIMENTAL DESIGN - All of the testing took place in the Anthropometry and Biomechanics Facility (ABF) at NASA – Johnson Space Center. The main objective of this study was to test the subjects at a variety of velocities, and determine the subsequent effects on fatigue. The study was designed to test each of the eight subjects at four different velocities—60 degrees/second, 120 degrees/second, 180 degrees/second, and 240 degrees/second. Each subject participated in three trials at each velocity, for a total of 12 trials per subject. One trial was conducted per testing day, with a minimum of 24 hours between testing days for each subject.

For the purpose of this study, "fatigue" was considered to be 30% of the subject's MVC. At the point where both the knee flexion and extension fell below the 30% fatigue line, the trial would be terminated. Another limit of five minutes was also established for each trial. If the subject's torque output was still above 30% of their MVC after five minutes, the trial would be terminated before fatigue was reached.

EXPERIMENTAL PROCEDURE - In an effort to ensure physical flexibility, the subjects were asked to wear shorts and a t-shirt for each of their trials. This also aided in the collection of video and anthropometric data because of being able to directly view their joint motion.

For each trial, the subject would sit in the LIDO Multi-Joint II chair and the test conductor would adjust the chair back to be flush with the subject's back, while the subject's knees were flush with the end of the seat bottom. The test conductor would then restrain the subject with a waist strap, and would isolate the right knee joint by strapping back the left ankle. The LIDO ankle cuff, attached to the dynamometer, was then securely fastened to the subject's right ankle. When the subject was at the point of full extension, a thigh restraint was placed on the right thigh to further isolate the joint.

The LIDO Multi-Joint II was configured for the desired velocity, and was set in concentric/concentric mode. This required the subject to move the arm of the dynamometer with his or her own force, hence significantly decreasing the risk of injury due to joint over-extension.

During each trial, three sets of data were collected. During a short warm-up period, the subject was asked to resist the motion of the dynamometer in the directions of both flexion and extension. The subject was then asked to relax and baseline data was acquired. After a verbal cue from the test conductor, the subject then began the maximum torque trial with the motion of flexion. This data was collected in the concentric/concentric mode. The maximum trial was concluded after three iterations of flexion and extension via a vocal command by the test conductor. The subject was then given a five-minute rest period. Wretling, et al [14] discovered an increase in mechanical output and electromyographic parameters during a fatigue trial in the first three maneuvers, and therefore recommend the maximum contraction be performed prior to the fatigue trial.

At the conclusion of the five minutes, the video recorder was activated, and the subject was asked to begin the fatigue trial, starting with knee flexion again. At this time, the test conductor activated both the LIDO software and the additional data acquisition computer to collect fatigue data. The subject performed the knee flexion/extension exercise until he or she either reached 30% of MVC, or five minutes expired. At this point, the videotape was stopped, and the restraints were removed from the subject. The subject then completed a short questionnaire concerning perceived exertion and motivation levels.

This procedure was repeated for all eight subjects during each of their 12 trials, for a total of 96 trials.

At the conclusion of the subject's 12^{th} and final test day, anthropometric measurements were taken. Weight, stature, hip height, knee height, ankle height, hip breadth, thigh circumference, and calf circumference measurements were taken from each of the subjects. Although this data was not directly used in the data analysis of this study, it could be helpful in using this data to generate a fatigue computer model.

DATA TREATMENT - The raw data collected from the data acquisition computer was in columnar text file format. These columns contained time, torque, and angle data, respectively. Three files were created per trial. A separate file was written for baseline data, maximum output data, and fatigue data.

For the purposes of analysis, each of the files was opened into a Microsoft Excel spreadsheet format and analyzed using spreadsheet tools.

ANALYSIS - Two different methods of analysis were used with the data collected in this study. Both the subject's decline in maximum torque over time, and the subject's change in torque at different points of a single iteration as they reached fatigue were of interest in this study.

To analyze the change in maximum torque over time, torque data was collected at the beginning and during the last three iterations of each fatigue trial. This data was averaged for each velocity, and the coefficient of variation was taken to assure that each trial was representative of the general trend of data so as not to skew the average. For each velocity, the maximum average torque and end average torque were compared to determine the percent to which the subject had fatigued. Figure 1 shows the percent fatigue per subject for extension. Figure 2 shows the percent fatigue per subject for flexion. Figure 3 shows the overall percent fatigue for extension. Figure 4 shows the overall percent fatigue for flexion.

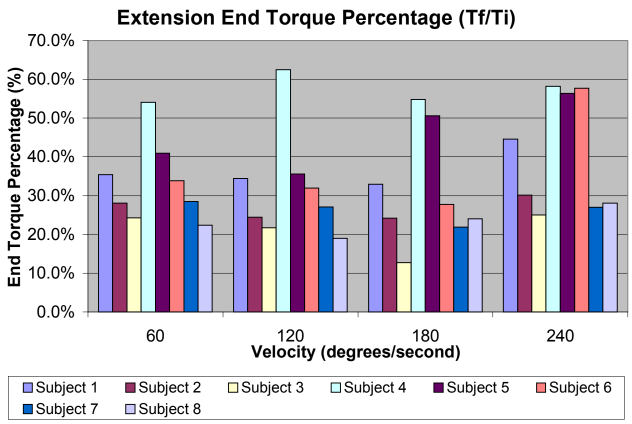

Figure 1. Extension End Torque Percentage by Subject

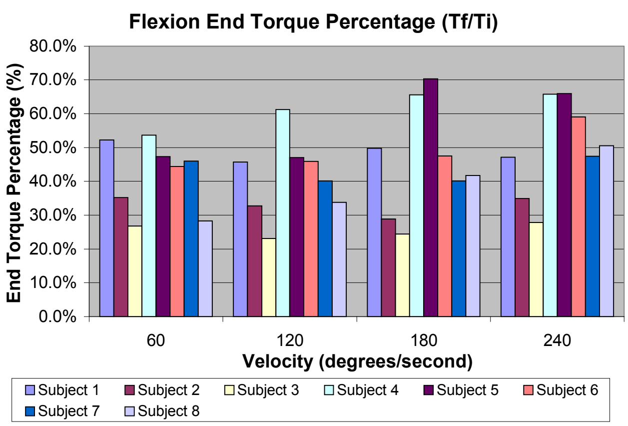

Figure 2. Flexion End Torque Percentage by Subject

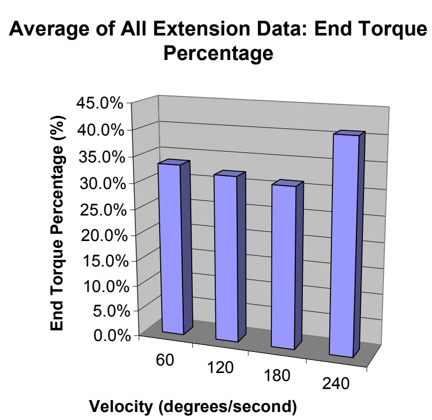

Figure 3. Overall Extension End Torque Percentage

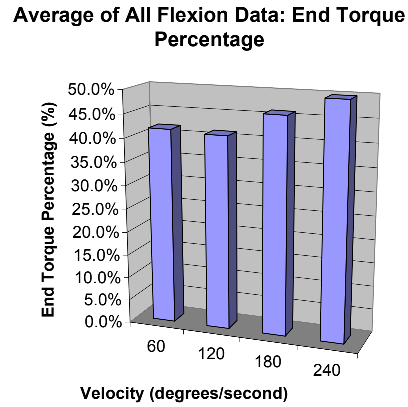

Figure 4. Overall Flexion End Torque Percentage

To analyze the change in torque at different points, or angles, of a single iteration, subject data was analyzed at three different stages of the fatigue trial. Although data was collected throughout the entire five minute trial, single iterations were extracted from the data file at starting time (t = 0), halfway through the trial (t = final time/2), and at the end of the trial (t = final time). Data taken at the beginning is referred to as *maximum data*, data taken at the halfway point is referred to as *interval data*, and data taken at the end is referred to as *end data*. The extracted data was visually edited to remove extraneous data points. Because the final time for most of the subjects was five minutes, the interval data was usually taken at 2.5 minutes and the end data was usually taken at five minutes. For subjects who reached fatigue before five minutes elapsed, their average final time for a given velocity was calculated, and this was used as the time for interval data and end data calculations.

For each stage of the data collection—maximum, interval, and end—one iteration was extracted from each set of data. For all three trials of a given velocity, the torque versus angle data was graphed, and then fit to a polynomial regression curve. The regression curves were then compared in a variety of graphical representations. First, the four different velocities were plotted for each subject. See Figure 5 for an example. Second, every subject's regression curves were plotted per velocity for each analysis stage. See Figure 6 for an example. Next, all of subjects' data were summarized into graph comparing extension and flexion per velocity. See Figure 7 for an example. Finally, all three data analysis stages—maximum, interval, and end—were compared graphically by velocity. See Figure 8 for an example.

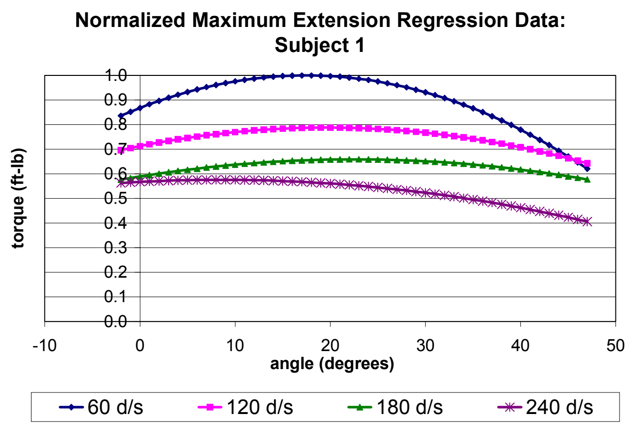

Figure 5. Sample of Regression Comparison By Subject

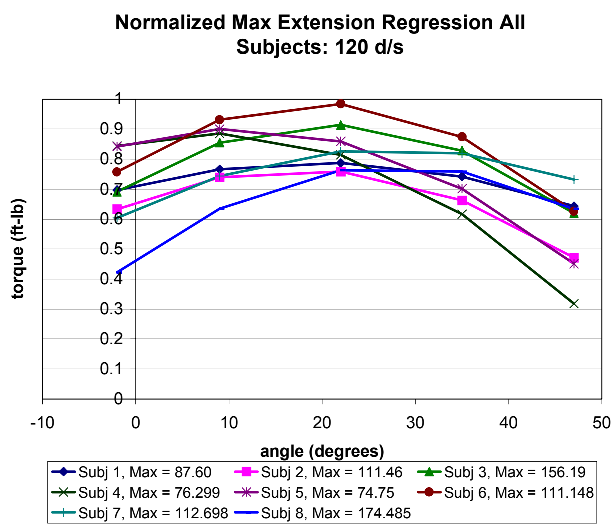

Figure 6. Sample of Regression Comparison by Velocity

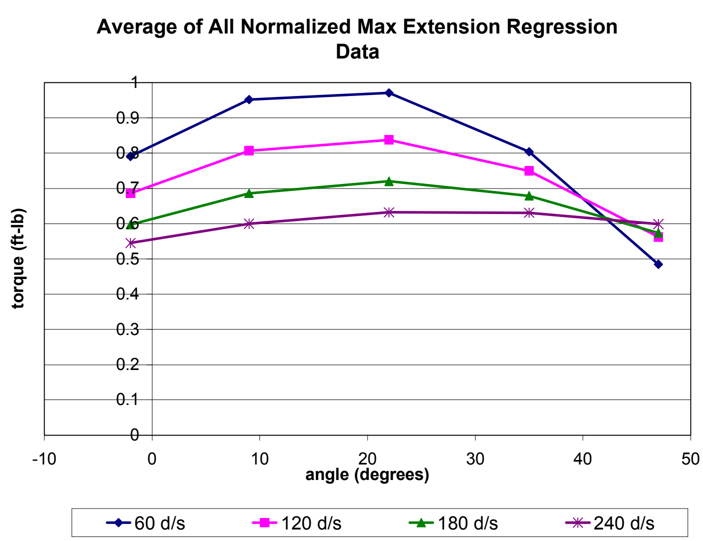

Figure 7. Sample of Overall Regression Comparison by Velocity

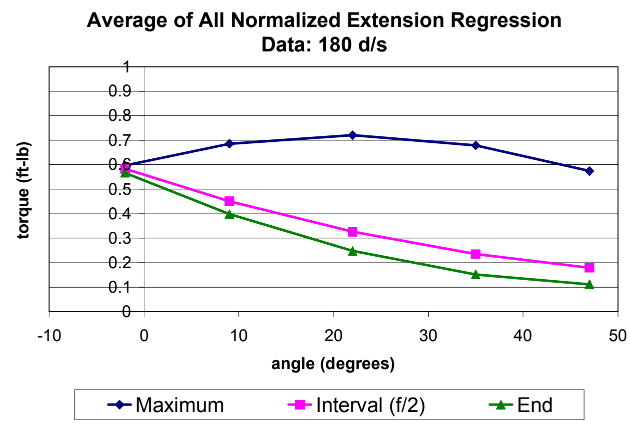

Figure 8. Sample of Overall Regression Comparison for All Stages per Velocity

RESULTS

END TORQUE PERCENTAGE – "End torque percentage (ETP)" refers to the percentage of the MVC that the subject was able to output at the conclusion of the trial. Because of this, a higher percentage number actually signifies a lower level of fatigue. The end torque percentage (ETP) analysis was done separately for knee extension and flexion. The ETP data for each subject was averaged with respect to velocity and graphed accordingly. Figures 1 and 3 show results from the extension trials. See Table 1 for the average extension ETP calculations. The extension data showed that for 60, 120, and 180 degrees per second, the ETP remained between 30% - 35%; however, for 240 degrees per second, the ETP escalated to over 40%. From this data the conclusion can be drawn that at a higher velocity, the fatigue the subject experiences in the direction of extension is minimized. Whether or not this trend would continue at higher speeds is unknown.

Average End Torque Percentage		
Velocity	ETP (%)	Fatigue Level (%)
60	33.4%	66.6%
120	32.1%	67.9%
180	31.1%	68.9%
240	40.9%	59.1%

Table 1. Average Extension End Torque Percentage (ETP)

The flexion ETP analysis showed similar results, however there seemed to be a significant increase in the ETP at 180 degrees per second. This incline continued at 240 degrees per second. In general, the subjects did not fatigue as severely during the motion of flexion. Average ETP for flexion ranged from 41.2% to 49.8%.

Figures 2 and 4 display ETP trends for flexion. See Table 2 for the average flexion ETP calculations.

Average End Torque Percentage		
Velocity	ETP (%)	Fatigue Level (%)
60	41.7%	58.3%
120	41.2%	58.8%
180	46.0%	54.0%
240	49.8%	50.2%

Table 2. Average Flexion End Torque Percentage (ETP)

The higher ETP calculations for flexion were somewhat unexpected. Throughout the entire testing process, the subjects commented about substantial pain in the hamstring area after flexion, and about the increased difficulty of flexion in comparison to extension. The high level of ETP of flexion may be attributed to the subjects making a more concerted effort during flexion.

Overall, the ETP analysis suggested that fatigue levels will lessen at higher velocities. This theory could be more substantially proven if this study were extended to cover a higher range of velocities.

TORQUE VERSUS ANGLE REGRESSION ANALYSIS - Extension regression data was compared both by velocity and by testing stage (maximum, interval, or end). In general it was found that there was very little decline or change in torque throughout a single iteration at 60 degrees per second over time. At the higher velocities, however, this change was more substantial. In general the torque output at the end of the iteration, at angles greater than 30^{o}, significantly decreased at higher velocities as time progressed. In addition, the overall torque at 120, 180, and 240 degrees per second decreased significantly between the maximum and interval stages. The decrease was much more severe for trials at 180 and 240 degrees per second than that for 120 degrees per second. The difference of the torque output at these higher velocities between the interval and end stages, however, was very minimal. At the higher velocities, the regression lines seem to flatten and maintain a more constant torque (see Figure 7).

Flexion regression data was analyzed with the same methods as extension, and came to very similar conclusions. Overall there was little change in torque output over time at 60 degrees per second. Again, there was a substantial decrease in torque at the interval and end stages for 120, 180, and 240 degrees per second, with the most significant decrease occurring at 180 and 240 degrees per second. Flexion data over time appeared to be the inverse of that of extension. The torque output at the interval and end stages was significantly lower at the beginning of the iteration, at angles between 0^{o} and 20^{o}. In addition, there was a noticeable increase in the torque output at the end of the flexion iteration at higher velocities. This can be seen in Figure 9. A similar, but not as significant, phenomenon occurred during the extension portion of the iteration. The flexion data also flattened at higher velocities, suggesting that the subject was able to maintain a more constant torque during a given range of motion (ROM) at a higher velocity.

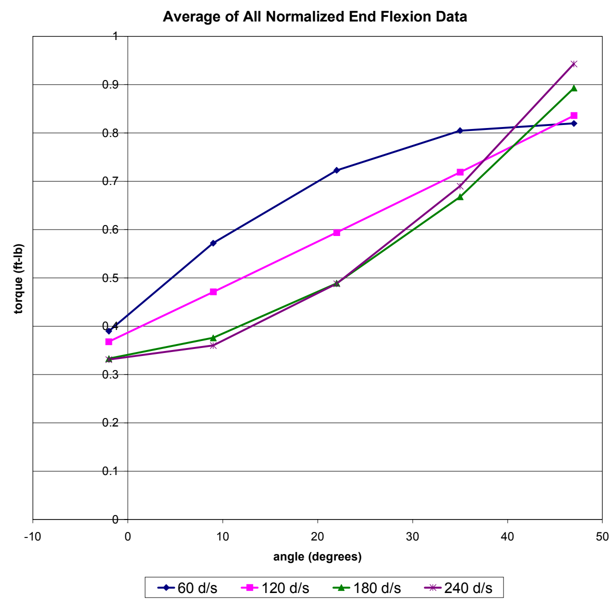

Figure 9. Summary of All End Flexion Data

DISCUSSION

At the conclusion of this study, much information has been gathered about the effects of velocity on torque when driven to fatigue. First, the original test plan and hypothesis assumed that the subjects would reach 30% of their MVC before the five minutes elapsed. However, for the vast majority of the subjects this proved incorrect. Most of the subjects fatigued to a certain level, approximately 40% of their MVC, and then sustained this torque level for the remainder of the trial. The regression curves comparing the three stages of analysis at a given velocity (see Figure 8) show that there is little decrease in overall torque between the interval and end analysis stage. This is believed to verify the “plateau phenomenon” where subjects decrease in torque rapidly and then plateau at a certain level and are able to maintain that torque for an extended period of time. Because this study terminated the trial at five minutes, it is inconclusive how long this plateau would sustain. An additional study, which exercises subjects for a longer period of time, would be very beneficial in establishing time limits for certain levels of fatigue.

Another observation from the data analysis showed that the subjects did not fatigue as severely at higher velocities. For extension, the data showed that velocities of 240 degrees per second or higher created a significantly lower level of fatigue for the subject. For flexion, the data showed this same result for velocities of 180 degrees per second or higher. This leads to the general statement that activities performed at a higher velocity are going to be less strenuous for a subject to perform over an extended period of time.

The ability of the subjects to maintain a given torque throughout an entire ROM was very accurate at high velocities during the beginning of each trial, before a time elapse. The low accuracy of torque at lower velocities can be explained based on research by Westing *et al* [15]. Data from this study suggests that non-maximal activation may occur under slow-velocity concentric loading. This is based on a decreased level of EMG activity at lower concentric velocities.

In the current study, the subjects' ability to maintain this constant torque diminished once time progressed and the subjects fatigued. By the interval and end stage evaluations, subjects were not able to maintain a steady torque throughout a ROM at any velocity.

Although the subject was less fatigued after five minutes at higher velocities, there was a much sharper decline in torque over time during these trials. At 60 degrees per second, there was a very gradual decline in torque, but the subject was usually nearing 30% MVC at the end of the trial. At 120, 180, and 240 degrees per second, the subject quickly decreased in torque from the maximum, but was able to maintain this decreased torque at a higher level throughout the five minutes. This finding could have implications on short duration activities. While the higher velocities appear to be more efficient in the fatigue aspect, maintaining a high torque for a short period of time is much more feasible at a lower velocity.

More conclusive results could be gained if this study was extended to both higher velocities and a longer time frame for exercise. Five minutes was a limiting factor in the data collection for this study, and should be extended if further studies were attempted in this area. In addition, testing subjects at higher velocities than 240 degrees per second may provide better insight to the relative efficiency of high velocities.

CONCLUSION

During spaceflight, all activity occurs at low velocities so the crewmembers are able to maintain control of their motions. Although the results of this study show a lower fatigue level at high velocities, this is not a feasible solution in a zero-gravity, low-resistance environment such as space. In accordance with the inverse relationship between torque and velocity, flight planners and hardware engineers can achieve similar reduced-fatigue results by decreasing the required torque for EVA or IVA. Because the average EVA lasts six hours, the ability to sustain long duration effort is paramount to EVA astronauts. By building hardware that can be manipulated at a low torque, hardware and suit engineers can provide an environment with a significantly reduced fatigue potential for the astronauts. This decreases the astronauts' chance of injury, and increases the efficiency of the mission.

When designing hardware for an EVA and developing mission plans, astronauts should not be expected to perform above 50% of their MVC at any time. This study found that most subjects reached a torque output plateau near 40% of their MVC. This minimum fatigue level should be given serious consideration in design and when planning for an EVA.

At a low speed, this study found that the inverse relationship between torque and velocity was maintained as the subject reached fatigue. Because all EVA and IVA activity occurs at low velocities, this finding eliminates velocity as a variable in space fatigue studies and simulations.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ABF: Anthropometry and Biomechanics Facility

ASCAN: Astronaut Candidate

CTSD: Crew and Thermal Systems Division

EMU: Extravehicular Mobility Unit

ETP: end torque percentage

EVA: extravehicular activity

FCSD: Flight Crew Support Division

GRAF: Graphics Research and Analysis Facility

IVA: intravehicular activity

MVC: maximum voluntary contraction

NASA: National Aeronautics and Space Administration

PABF: Precision Air Bearing Facility

ROM: range of motion